Analyzing Energy Use with Decomposition Methods

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Discussion

- Energy consumption and energy efficiency?

- How can energy consumption be disaggregated?

- Categorization of energy consumption across end-use sectors?
Goal of this training session

provide tools and best practices in decomposition analysis to rapidly and efficiently adopt decomposition methods on national levels
Purpose of decomposition

- Quantify relative contributions of the pre-defined factors to the change in energy consumption
- Track down the origin in energy consumption variations
- Measure effectiveness of energy policy and technology
Disaggregation of energy consumption

The changes in energy use within a sector are separated in various components:

\[ E = \sum_{i} A \cdot \frac{A_i}{A} \cdot \frac{E_i}{A_i} = A \cdot \sum_{i} (S_i \cdot I_i) \]

- **Aggregate activity** \( A \)
  - value-added for manufacturing industry and services; population in the household sector; or as passenger-kilometres and tonne-kilometres, respectively, for the passenger and freight transport sectors
- **Sectoral structure** \( S \)
  - mix of activities within a sector and further divides activity into industry sub-sectors, measures of residential end-use activity or transportation modes
- **Energy intensity** \( I \)
  - energy use per unit of activity
<table>
<thead>
<tr>
<th>Sector</th>
<th>Sub-sector</th>
<th>Activity (A)</th>
<th>Structure (S)</th>
<th>Intensity (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households</td>
<td></td>
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<tr>
<td></td>
<td>Space Heating</td>
<td>Population</td>
<td>Floor Area/Population</td>
<td>Space Heating Energy&lt;sup&gt;1&lt;/sup&gt; /Floor Area</td>
</tr>
<tr>
<td></td>
<td>Water Heating</td>
<td>&quot;</td>
<td>Population/Occupied Dwellings</td>
<td>Water Heating Energy&lt;sup&gt;2&lt;/sup&gt; /Occupied Dwellings</td>
</tr>
<tr>
<td></td>
<td>Cooking</td>
<td>&quot;</td>
<td>Population/Occupied Dwellings</td>
<td>Cooking Energy&lt;sup&gt;2&lt;/sup&gt; /Occupied Dwellings</td>
</tr>
<tr>
<td></td>
<td>Lighting</td>
<td>&quot;</td>
<td>Floor Area/Population</td>
<td>Lighting Energy /Floor Area</td>
</tr>
<tr>
<td></td>
<td>Appliances</td>
<td>&quot;</td>
<td>Appliances Ownership/Population</td>
<td>Appliances Energy / Appliances Ownership</td>
</tr>
<tr>
<td>Passenger Transport</td>
<td>Car</td>
<td>Passenger-kilometre</td>
<td>Share of Pass-kilometre</td>
<td>Energy/Pass-kilometre</td>
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<td></td>
<td>Bus</td>
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<td>Rail</td>
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<td></td>
<td>Domestic Air</td>
<td>&quot;</td>
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<tr>
<td>Freight Transport</td>
<td>Truck</td>
<td>Tonne-kilometre</td>
<td>Share of Tonne-kilometre</td>
<td>Energy/Tonne-kilometre</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>&quot;</td>
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<tr>
<td></td>
<td>Domestic Shipping</td>
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</tr>
<tr>
<td>Manufacturing</td>
<td>Food, Beverages &amp; Tobacco</td>
<td>Value-added</td>
<td>Share of Value-added</td>
<td>Energy/Value-added</td>
</tr>
<tr>
<td></td>
<td>Paper, Pulp &amp; Printing</td>
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<td>Chemicals</td>
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<td>Non-metallic Minerals</td>
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<td></td>
<td>Primary Metals</td>
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<tr>
<td></td>
<td>Metal Products &amp; Equipment</td>
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<td></td>
<td>Other Manufacturing</td>
<td>&quot;</td>
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<td>&quot;</td>
</tr>
<tr>
<td>Services</td>
<td>Services</td>
<td>Value-added</td>
<td>Share of Value-added</td>
<td>Energy/Value-added</td>
</tr>
<tr>
<td>Other Industries&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Agriculture &amp; Fishing</td>
<td>Value-added</td>
<td>Share of Value-added</td>
<td>Energy/Value-added</td>
</tr>
<tr>
<td></td>
<td>Construction</td>
<td>&quot;</td>
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<td>&quot;</td>
</tr>
</tbody>
</table>

<sup>1</sup> Adjusted for climate variations using heating degree-days.
<sup>2</sup> Adjusted for household occupancy.
<sup>3</sup> The following ISIC groups are not included in the analysis: 10 – 14 Mining & Quarrying; 23 Fuel Processing; and 40 – 41 Electricity, Gas & Water Supply. Industries in category “Other industries” are analysed only to a very limited extent in this study.
Decomposition components

- **Activity effect** $E_t^A$
  The activity effect can be calculated as the relative impact on energy use that would have occurred in year $t$ if the structure and energy intensities for a sector had remained fixed at their base year values ($t=0$) while aggregate activity had followed its actual development.

- **Structure effect** $E_t^S$
  The structure effect is determined by making the calculation using constant aggregate activity and energy intensities but varying the sectoral structure.

- **Intensity effect** $E_t^I$
  The intensity effect is calculated by assuming that the sectoral structure and aggregate activity for a sector had remained fixed at the base year values while energy intensities had followed their actual development.
Discussion of results: Passenger Transport

Figure 6.22 ➤ Decomposition of Changes in Car Energy Use per Capita, 1990 – 2004

Note: Austria and Ireland are excluded due to the lack of complete time series data for vehicle-kilometres.
Discussion of results: Service sector

Figure 5.10  Decomposition of Changes in Service Sector Energy Intensity, 1990 – 2004
Mathematical derivation

- Goal: decompose energy consumption so that $\varepsilon$ is minimal
  \[ \Delta E = E_t - E_0 = \Delta A + \Delta S + \Delta I + \varepsilon \]

- Change in energy consumption:
  \[ E = \sum_i A_i S_{i,t} I_{i,t} \]
  \[ \frac{d}{dt} \]
  \[ \Leftrightarrow \frac{\partial E_t}{\partial t} = \sum_i \frac{\partial A_i}{\partial t} S_{i,t} I_{i,t} + \sum_i \frac{\partial S_{i,t}}{\partial t} A_i I_{i,t} + \sum_i \frac{\partial I_{i,t}}{\partial t} A_i S_{i,t} \]
  \[ \Leftrightarrow \ln \left( \frac{E_t}{E_0} \right) = \int_0^t \sum_i \frac{\partial A_i}{\partial t} \frac{S_{i,t} I_{i,t}}{E_0} dt + \int_0^t \sum_i \frac{\partial S_{i,t}}{\partial t} \frac{A_i I_{i,t}}{E_0} dt + \int_0^t \sum_i \frac{\partial I_{i,t}}{\partial t} \frac{A_i S_{i,t}}{E_0} dt \]

- Fortunately we do not need to solve this equation, but various methods have been developed to do so.
Overview of existing methods

\[ \Delta E = E_t - E_0 = \Delta A + \Delta S + \Delta I + \varepsilon \]

- \( \varepsilon \) is a residual whose magnitude depends on the decomposition method

- Common methods
  - Laspeyres method
  - Paasche index
  - Simple average divisia method (arithmetic mean or Törnqvist formulation)
  - Fischer Ideal
  - Parametric Divisia Method I (PMD I) and II (PMD II)
  - Log Mean Divisia I (LMD I) and II (LMD II)
## Evaluation of existing methods

<table>
<thead>
<tr>
<th>Index</th>
<th>Perfect decomposition</th>
<th>Time reversible</th>
<th>Subsectors additive</th>
<th>Easy to understand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paasche</td>
<td>no</td>
<td>no</td>
<td>YES</td>
<td>very easy</td>
</tr>
<tr>
<td>Simple Laspeyres</td>
<td>no</td>
<td>no</td>
<td>YES</td>
<td>very easy</td>
</tr>
<tr>
<td>Refined Laspeyres</td>
<td>YES</td>
<td>no</td>
<td>YES</td>
<td>moderately</td>
</tr>
<tr>
<td>Fischer Ideal</td>
<td>YES</td>
<td>YES</td>
<td>No</td>
<td>moderately</td>
</tr>
<tr>
<td>Simple average/ arithmetic mean/ divisia (Törnqvist)</td>
<td>no</td>
<td>YES</td>
<td>No</td>
<td>moderately</td>
</tr>
<tr>
<td>Adjusted PMD I and II</td>
<td>no</td>
<td>YES</td>
<td>YES</td>
<td>difficult</td>
</tr>
<tr>
<td>LMD I</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>moderately</td>
</tr>
<tr>
<td>LMD II</td>
<td>YES</td>
<td>YES</td>
<td>no</td>
<td>moderately</td>
</tr>
</tbody>
</table>

### Laspeyres and LMD I are the preferred methods

- Laspeyres for its ease of understanding, especially to non-experts, but the existence of an interaction term is a drawback
- LMD I for its theoretical soundness
Laspeyres

- easy to communicate
- interaction term

<table>
<thead>
<tr>
<th></th>
<th>Additive</th>
<th>Multiplicative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity Effect</td>
<td>$E^A_t = A_t \sum_i S^i_0 I^i_0 - E_0$</td>
<td>$E^A_t = \frac{A_t \sum_i S^i_0 I^i_0}{E_0}$</td>
</tr>
<tr>
<td>Structural Effect</td>
<td>$E^S_t = A_0 \sum_i S^i I^i_0 - E_0$</td>
<td>$E^S_t = \frac{A_0 \sum_i S^i I^i_0}{E_0}$</td>
</tr>
<tr>
<td>Intensity Effect</td>
<td>$E^I_t = A_0 \sum_i S^i_0 I^i_t - E_0$</td>
<td>$E^I_t = \frac{A_0 \sum_i S^i_0 I^i_t}{E_0}$</td>
</tr>
</tbody>
</table>
LMD I

- no interaction term
- more difficult to communicate to non-experts
- Method not defined for zeros or negative numbers in data

<table>
<thead>
<tr>
<th>Effect</th>
<th>Additive</th>
<th>Multiplicative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity Effect</td>
<td>$E_{i}^{A} = \sum_{i} L(E_{i}', E_{i}^{0}) \ln \left( \frac{A_{i}'}{A_{i}^{0}} \right)$</td>
<td>$E_{i}^{A} = \exp \sum_{i} \left( \frac{L(E_{i}', E_{i}^{0})}{L(E', E^{0})} \ln \left( \frac{A_{i}'}{A_{i}^{0}} \right) \right)$</td>
</tr>
<tr>
<td>Structure Effect</td>
<td>$E_{i}^{S} = \sum_{i} L(E_{i}', E_{i}^{0}) \ln \left( \frac{S_{i}'}{S_{i}^{0}} \right)$</td>
<td>$E_{i}^{S} = \exp \sum_{i} \left( \frac{L(E_{i}', E_{i}^{0})}{L(E', E^{0})} \ln \left( \frac{S_{i}'}{S_{i}^{0}} \right) \right)$</td>
</tr>
<tr>
<td>Intensity Effect</td>
<td>$E_{i}^{I} = \sum_{i} L(E_{i}', E_{i}^{0}) \ln \left( \frac{I_{i}'}{I_{i}^{0}} \right)$</td>
<td>$E_{i}^{I} = \exp \sum_{i} \left( \frac{L(E_{i}', E_{i}^{0})}{L(E', E^{0})} \ln \left( \frac{I_{i}'}{I_{i}^{0}} \right) \right)$</td>
</tr>
</tbody>
</table>

$L(a,b) = \frac{a-b}{\ln a - \ln b}$ with $a,b > 0$ and $a \neq b$
Exercise session: end-use

- Perform complete decomposition using Laspeyres and LMDI
- Calculate the activity, structure and intensity effect of the given dataset for the manufacturing sector
- Compare results from LMDI and Laspeyres
**Fixed vs. rolling base year decomposition**

For every method, two decomposition schemes exist:

- **Fixed base year or non-chained decomposition**
  - change in energy consumption between base year 0 and final year $T$
  - + data for all intermediate years not required

- **Rolling base year or chained decomposition**
  - yearly change in energy consumption between base year 0 and 1, year 1 and 2, ... year $T$-1 and $T$ and finally chaining of results
  - + more precise
Commodity correction

- In the industrial sector, the best measure of activity is physical units of production (e.g. tones of pulp, liters of beer).
- These units are difficult to compare, but they are a better indicator of activity.
- No constant relation between value added (GDP) and physical units exist, as changes in price influence the relationship. The activity can be corrected as follows:

\[
A_i = P_i^0 \cdot \frac{V_i^t}{V_i^0}
\]

P: GDP output; V: physical unit; i: subsector; t: current year; 0: base year

- IEA collects commodity data for cement, steel, pulp and paper currently: no correction performed, but recommended.
Weather correction

The impact of weather should be considered in household heating and cooling:

- Correction for weather for space heating energy
  \[ E_{-SH} = \frac{E_{SpaceHeating}}{1 - \sigma_{heat}(1 - \tau_{heat,i})} \]

- Correction for weather for space cooling
  \[ E_{-SC} = \frac{E_{SpaceCooling}}{1 - \sigma_{cool}(1 - \tau_{cool,i})} \]

- Correction for weather
  \[ E_W = E_{-SH} + E_{-SC} \]

\( \sigma_{heat/cool} \) heating/cooling elasticity for adjusting heating requirements
\( \tau_{heat, i/cool, i} \) heating/cooling index of variance from average requirements by year i (e.g. heating/cooling degree days in current year compared to average from 30 past years)

IEA assumptions
- only heating considered
- \( \sigma_{heat} \) assumed 1 (probably around 0.75)
- HDD_{30 past years} = 2700 (global average)
Generation efficiency

- Fossil fuels (coal, gas, oil)
- Main activity producer electricity plants and main activity producer CHP plants

Efficiency $E$: 

$$
E = \frac{\text{energy output}}{\text{energy input}}
$$

- Energy input: net calorific values (estimated using the lower heating value LHV)
- Energy output: gross production of electricity and heat. auxiliary electricity consumption and losses in transformers are included
Generation efficiency: correction for CHP

Efficiency

- the extraction of heat reduces the electric efficiency
- but increases the overall (electrical and thermal) efficiency

Formula:

$$E = \frac{P + H \times s}{I}$$

- $P$: electricity production from public electricity plants and public CHP plants
- $H$: heat output from public CHP plants
- $s$: correction factor between heat and electricity, defined as the reduction in electricity per unit of heat extracted. $S=0.15-0.2$ (Phylipsen, 1998)

- $I$: fuel input for public electricity plants and public CHP plants
Exercise: generation efficiency

- Calculate the energy efficiencies for 4 selected countries
- Compare the average efficiencies between 1990-1994 and 2004-2008
- Determine the potential fuel savings
Take-away messages

- Decomposition analysis is essential to analyze energy efficiency in end-use sectors
- Energy consumption can be decomposed in Activity (A), Structure (S) and Intensity (I)
  \[ E = A \cdot \sum_{i}^{n} (S_i \cdot I_i) \]
- LMD I preferred method
- Fixed base-year vs. rolling base year (depending on available data)
- Correction for cooling should be considered in warm regions
References

- IEA, Energy Use in the New Millennium, 2007
- IEA, IEA Scoreboard, 2011
- ABARE, End-use energy intensity in the Australian economy, 2010
- M.K. Jaccard and Associates, Improvement of the OEE/DPAD decomposition methodology, 2005
- B.W. Ang, Decomposition analysis for policymakers in energy: which is the preferred method? 2003
Discussion of results: Manufacturing

Figure 3.16: Decomposition of Changes in Manufacturing Energy Intensity, 1990 – 2004
Discussion of results: Household heating

Figure 4.16 Decomposition of Changes in Space Heating per Capita, 1990 – 2004